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Effect of mulch, irrigation, and soil type on water use and yield of maize

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Abstract

Tillage practices that maintain crop residues on the soil surface help reduce evaporation of soil water, which can benefit high water use crops such as maize (*Zea mays* L.). Management practices, climatic conditions, and soil type may affect how well a crop responds to surface residue. We conducted experiments with short season maize in 1994 and 1995 in Bushland, TX, USA, utilizing a rain shelter facility that has lysimeters containing monolithic cores of the Pullman (fine, mixed, thermic Torrertic Paleustolls), the Ulysses (fine-silty, mixed, mesic Aridic Haplustolls), and the Amarillo (fine-loamy, mixed, thermic Aridic Paleustalfs) soil series. In 1994, the treatments were a flat wheat (*Triticum aestivum* L.) straw and coconut (*Cocus nucifera* L.) fiber mulch of 4 Mg ha^{-1} with infrequent irrigations totaling 25% and 75% of long-term average rainfall for the growing season (200 mm). The 1995 treatments were similar, but used a heavier mulch of 6.7 Mg ha^{-1} and more frequent irrigations totaling 60% and 100% of long-term average rainfall. The mulch was applied at the 3-leaf growth stage. Mean potential grass reference evapotranspiration for the vegetative and reproductive growth stages in 1994 was 6.6 and 6.3 mm day^{-1}, respectively, and in 1995 it was 6.8 and 7 mm day^{-1}, respectively. The mulched and bare soil surface treatments used similar amounts of water in each year. In 1994, mulch did not affect yield, yield components, or leaf area index (LAI). No significant differences occurred in plant available water (PAW) between mulched and bare soil treatments from emergence through harvest. In 1995, mulch increased grain yield by 17%, aboveground biomass by 19%, and grain water use efficiency (WUE) by 14% compared with bare soil treatments. Mulched treatments also maintained significantly greater PAW compared with bare soil treatments until near anthesis and, after anthesis, LAI was significantly greater in the mulched treatments compared with the bare soil treatments. In 1995, mulch significantly increased grain yield and grain WUE of the maize crop in the Pullman soil, grain yield and biomass WUE of the crop in the Amarillo soil, and had no significant effect on the crop in the Ulysses soil compared with the bare soil treatments. The significant increase in water use efficiency in 1995 was the result of soil water being used for crop growth and yield rather than in evaporation of soil water. The more favorable soil water regime in 1995 compared with 1994 between the mulched and bare soil treatments was possibly due to the higher evaporative demand environment, the increase in mulch mass, and the increased irrigation frequency. This was especially important in soils where textural characteristics affected both rooting and soil water extraction by maize which limited its ability to tolerate water stress. © 1999 Published by Elsevier Science B.V.

Keywords: Residue management; Mulch; Evapotranspiration; Lysimeter; Water use efficiency

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1. Introduction

A more efficient use of the region's declining irrigation water and limited precipitation will help sustain agricultural production in the semi-arid central and southern high plains of the USA. Maize (*Zea mays* L.), a major irrigated crop in that area (Musick et al., 1990), has a high seasonal water requirement for maximum yields (Musick and Dusek, 1980). Due to increased pumping costs and declining water levels in an aquifer used for irrigation, maize producers need to adopt tillage practices that limit evaporative losses and increase crop water use efficiency.

Tillage practices that maintain crop residue on the soil surface have been shown to increase maize yields in numerous studies (e.g., Triplett et al., 1968; Lal, 1974, 1978, 1995; Unger, 1986; Wicks et al., 1994). The yield increases were generally credited to increased water contents in the soil due to reduced evaporation. This additional soil water storage can occur during fallow periods prior to planting (Greb et al., 1967) as well as during the growing season (Greb, 1966; Adams et al., 1976). Lal (1974) found that maize grain yields increased by as much as 52% with mulch applied only after planting. However, Unger and Jones (1981) concluded that grain sorghum [*Sorghum bicolor* (L.) Moench] responded more to the soil water stored during fallow than to additional soil water conserved by mulch applied only during the growing season.

Residue reduces evaporation of soil water primarily by shading the soil surface from the sun. Shading is most effective during the first-stage drying of a wet soil surface (Bond and Willis, 1970; Adams et al., 1976). Evaporation reduction due to crop residue also diminishes with time, especially in periods of drought or infrequent, light rains (Greb, 1966; Lal, 1974). In a laboratory study using soil columns, Unger and Parker (1976) found that evaporation rates were higher for bare soil than for soil with surface residue for about the first 15 days, after which the trend reversed.

The plant canopy can also shade the soil surface, thus substituting for the beneficial effects of residue during latter part of the growing season (Adams et al., 1976; Unger and Jones, 1981). Todd et al. (1991) found that in a dryland maize crop, shading by the canopy accounted for at least three-fourths of the evaporation reduction, while under limited irrigation, residue and canopy contributed equally.

The amount or thickness of residue coupled with atmospheric evaporative potential determine the rate of drying. Greb (1966), Adams et al. (1976), and Unger (1976) reported notable evaporation reduction from wetted soil surfaces covered with about 4 Mg ha^{-1} of flat wheat (*Triticum aestivum*) straw. Bond and Willis (1970) found that first stage evaporation rate decreased with either increasing residue rates or decreasing evaporation rates. Unger and Parker (1976) and Steiner (1989) noted that residue thickness (volume) was more critical than mass per unit area for controlling evaporation. On a mass basis, about two times as much sorghum and four times as much cotton (*Gossypium hirsutum* L.) residues on the surface of the soil were needed to achieve the same evaporation reduction as with wheat straw. Under field conditions, Unger (1978) found that the average precipitation storage in a Pullman clay loam soil covered with 12 Mg ha^{-1} of wheat residue was over twice that without residue.

Maintaining residue on the soil surface has not always been shown to increase yields. Unger (1986) reported yield reductions with high residue amounts, which was due partially to low N fertility. Wicks et al. (1994) also had yield reductions due to cool, rainy weather. Multi-year studies showed a variable response to residue with each growing season, ranging from 0% up to 70% yield increases. As Wicks et al. (1994) pointed out, yield variations resulted from how long plant development was delayed due to lower soil temperatures, how much water was conserved, how much water stress occurred, the amount and distribution of precipitation, and evaporative demand.

Other variations in response have been credited to the soil type (Triplett et al., 1970; Gajri et al., 1994). Gajri et al. (1994) found that mulching increased maize grain yields from crops in loamy sand for all the 10 years studied, but that mulching decreased yields of maize grown in sandy loam some years and increased yields in other years compared with maize with bare soil surfaces. Triplett et al. (1970) reported that mulching increased yields of maize grown in a silt loam or in a sand, but decreased yields on the fine sandy loam.

In environments where there is limited or poorly distributed precipitation, declining water supplies for irrigation, and relatively high evaporative potential, improved water use efficiency is essential for successful maize farming. The interactive effects of limited irrigation, growing season mulch, and soil characteristics need to be better understood to achieve this objective. The objective of this research was to evaluate the effect of a growing season mulch on the growth, water use, and yield of maize grown in three soil types.

2. Materials and methods

2.1. Rain shelter and lysimeter facilities

Two experiments using a short-season maize were conducted at Bushland, TX, USA (35°11′N, 102°06′W; elevation 1170 m above mean sea level), in a 0.25 ha field with a rain shelter facility that had 36 weighable lysimeters, each containing a monolithic soil core of one of three soil types. The rain shelter was a 13 m×18 m×3.7 m high metal building with a control sensor that automatically initiated building movement over the lysimeters when the sensor caught about 1 mm of rain. The lysimeters had a surface dimension of 1.0 m×0.75 m, were 2.4 m deep, and contained monolithic soil cores 2.3 m deep. A drainage system was located in the bottom 0.1 m. The lysimeters were arranged in two pits with two rows of 12 lysimeters each that were side by side in each pit. The facility and monolithic core collection techniques were described in detail by Schneider et al. (1993).

2.2. Soils

Soil types were Pullman clay loam from Bushland, TX; Ulysses clay loam from Garden City, TX; and Amarillo sandy loam from Big Spring, TX. The Pullman soil was slowly permeable due to a strong, clay Bt horizon at about 0.18 m with a bulk density of 1.44 Mg m^{-2}, which was above a clay horizon at about 0.5 m with a bulk density of 1.5 Mg m^{-2}. Another transition occurred along a wavy boundary at about 1.4 m to an underlying calcic B horizon with lower bulk density and up to 50% $CaCO_3$ by mass.

The Ulysses soil had clay loam upper horizons with high silt contents that overlay silty clay loam horizons beginning at about 0.3 m. The C horizons of silt loam and silty clay began at about 0.7 m. The soil had uniform bulk density of 1.42 Mg m^{-3} throughout the profile. The Amarillo soil had an average sand content of 58%, and an average bulk density of 1.69 Mg m^{-3}. Sandy clay loam B horizons extended from about 0.2 to 2 m. The horizons contained up to 35% $CaCO_3$ below about 1 m. More complete soil descriptions were given in Tolk et al. (1998).

2.3. Experimental procedures

Response to growing season mulch was tested in two separate experiments in 1994 and 1995. The crops in the lysimeters were sowed by hand, and the area surrounding the lysimeters by conventional unit planters. Mulch was applied to one half of the lysimeters, while the other half remained bare. The mulch was a flat wheat straw and coconut (*Cocus nucifera* L.) fiber mat (SC150 erosion control blanket, North American Green,[1] Evansville, IN) approximately 1 cm thick in 1994 and 2 cm thick in 1995 which covered the entire soil surface. Mulch was applied at about the 3-leaf growth stage in both years. Agronomic and crop development information is summarized in Table 1.

Irrigation treatments are summarized in Table 2. In 1994, moderate mulch rates (4 Mg ha^{-1}) and infrequent irrigation treatments that totaled either 25% (I-25) or 75% (I-75) of long-term average rainfall (about 200 mm) for the cropping season (mid-May through mid-August) were applied. The I-25 treatment received a 50 mm irrigation at the mid-vegetative growth stage. The I-75 irrigations were applied in 50 mm increments at emergence, mid-vegetative, and pollination growth stages. The 1995 experiment had moderately high mulch rates (6.7 Mg ha^{-1}) and more frequent irrigation treatments totaling 60% (I-60) and 100% (I-100) of average rainfall. The I-60 treatment received 50 mm irrigations at the 8-leaf and mid-grain fill growth stages, and a 25 mm irrigation at tasseling. The I-100 treatment received 50 mm irrigations at the 8-leaf, early grain fill, and mid-grain fill growth stages, and 25 mm irrigations at tasseling and pollination. Irrigations were measured by hand using a

[1]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

Table 1
Agronomic and growth stage information for 1994 and 1995

	1994	1995
Variety	PIO-3737	PIO-3737
Population	4 plants m^{-2}	4 plants m^{-2}
Row Spacing	0.75 m	0.75 m
Fertilization	11 g (N), 6 g (P) m^{-2}	14 g (N), 6 g (P) m^{-2}
Growth Stages		
Planting	21 April (111)[a]	10 May (130)
Emergence	5 May (125)	22 May (142)
Anthesis	1 July (182)	22 July (203)
Harvest	29 August (241)	8 September (251)

[a]Day of year in parentheses.

graduated bucket and applied using buckets that slowly drained through the mulch, which wet the soil surface entirely.

Water contents of the soil were measured in each lysimeter by neutron scattering (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) at depth increments of 0.2 m starting at 0.1 m and ending at 2.1 m. The gauge was calibrated in situ at the Garden City, Big Spring, and Bushland monolith collection sites using techniques described by Evett and Steiner (1995). Separate calibration equations were developed for the A, Bt, and Bk horizons of the Pullman soil; A, Bt, and Btk horizons of the Amarillo soil; and A and lower horizons combined of the Ulysses soil.

Plant available water (PAW, in mm) was calculated as the water remaining in a 2.2 m profile above the lower limit of water extraction (LL) determined for grain by neutron scattering in a prior experiment (data not reported here). The lysimeters were generally weighed weekly to determine evapotranspiration (ET), which was calculated from the difference in lysimeter mass between weighings, plus any applied water infiltration minus any drainage water. Water use efficiency (WUE) was calculated as the ratio of grain yield or aboveground biomass and ET for the growing season. The lysimeters were drained from the bottom each year prior to planting with a vacuum pump operating at 0.06 MPa vacuum, and were checked for drainage three to four times during the cropping season.

Measurements of solar radiation, air temperature, relative humidity, precipitation, wind speed, and wind direction were taken at the rain shelter facility using a weather station (Model 012, Campbell Scientific, Logan, UT). The station was located at the corner of lysimeter pits that was downwind from the prevailing southwest wind direction. Potential grass reference ET (ET_0) was calculated using procedures outlined by Allen et al. (1989).

Dry matter and grain yield were measured by harvesting all of the plants in each lysimeter. Each treatment value is a mean of three 0.75 m^2 samples.

Table 2
Irrigation applications in 1994 and 1995 by soil type and irrigation treatment and plant available water at the 4-leaf growth stage (PAW1) and harvest (PAW2)

Soil series	1994						1995					
	I-25			I-75			I-60			I-100		
	Irr (mm)	PAW1 (mm)	PAW2 (mm)	Irr (mm)	PAW1 (mm)	PAW2 (mm)	Irr (mm)	PAW1 (mm)	PAW2 (mm)	Irr (mm)	PAW1 (mm)	PAW2 (mm)
Pullman												
No mulch	50	280	73	150	243	57	125	233	76	200	226	117
Mulch	50	285	82	150	266	77	125	245	14	200	245	97
Ulysses												
No mulch	50	440	119	150	397	114	125	258	−15	200	253	42
Mulch	50	434	138	150	398	121	125	272	−33	200	269	38
Amarillo												
No mulch	50	346	42	150	312	40	125	235	−2	200	236	15
Mulch	50	354	38	150	302	15	125	248	−28	200	245	35

Grain was removed from the cob by hand and dried at 70°C. Grain yield is reported at a water content of 0%.

Leaf area index (LAI) was measured by hand on all plants of selected lysimeters representing a range of soil and irrigation treatments. Leaf area was estimated as the sum of the products of the length and maximum width of every leaf, after which the sum was adjusted by multiplying it by 0.75, similar to procedures described by McKee (1964). LAI was calculated by dividing the leaf area by the surface area of the lysimeter (0.75 m^2). LAI for the remaining lysimeters was estimated from procedures similar to those described by Adams and Arkin (1977). Nadir photographs were projected onto a random dot grid, and the number of points intercepted by green leaf area recorded for a fraction green cover. A curvilinear relationship between intercepted grid dots and measured leaf area was developed for each year.

Soil types were randomly distributed within each pit, with three replications per soil type. Data were analyzed using general linear model procedures of SAS (SAS Institute, 1985). The model included irrigation, soil type, mulch, and the interaction. Irrigation treatments were tested separately using within replicates error term for the irrigation treatments. Mean separations were computed using the Ryan–Einot–Gabriel–Welsch multiple-range test, which controls type 1 experimental error.

3. Results

3.1. Environmental conditions

Evaporative demand in the two cropping seasons was greater in 1995 compared with 1994 (Fig. 1). In 1994, average reference ET_0 was 6.6 mm day^{-1} from emergence through anthesis, 6.3 mm day^{-1} from anthesis through harvest, with a seasonal average ET_0 of 6.5 mm day^{-1}. In 1995, average reference ET_0 was 6.8 mm day^{-1} from emergence through anthesis, 7 mm day^{-1} from anthesis through harvest, with a seasonal average of 6.9 mm day^{-1}.

3.2. Yield components

Mulch did not significantly affect yield components in 1994 (Table 3). Irrigation treatment did, however,

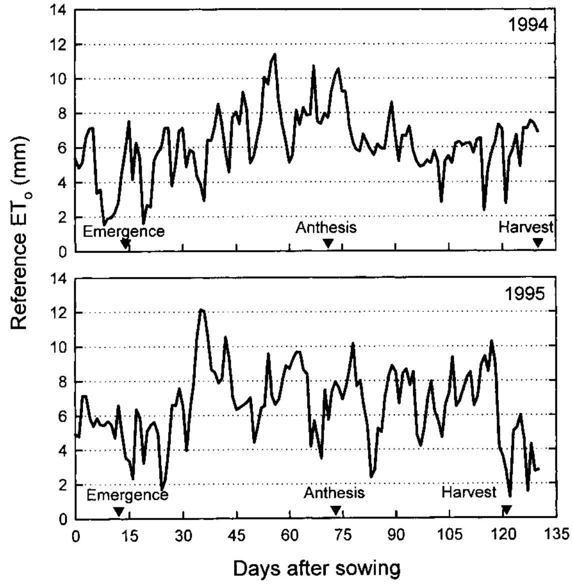

Fig. 1. Potential grass reference evapotranspiration (ET_0) for the 1994 and 1995 growing seasons.

with irrigation at the I-25 level significantly reduce grain yield by 19%, total biomass by 14%, and seed number and ET by about 11% compared with the I-75 treatment. The maize in the Ulysses soil produced the highest grain yield, biomass, and ET compared with the maize in the other two soils. Seed number and ET were lowest for the maize in the Pullman soil. No interactive main effects occurred.

In 1995, mulch significantly increased grain and biomass yields by about 20%, seed number and seed mass by about 10%, and grain yield and biomass by about 14% compared with treatments with a bare soil surface (Table 4). Cumulative ET was similar for bare and mulched surfaces. Irrigation treatment had no significant effect. As in 1994, the maize in the Ulysses soil produced the highest grain yield, biomass, and ET even though all the soils initially contained similar PAW (PAW1) (Table 2) and received the same amount of irrigation. The maize in the Pullman soil again produced the lowest seed numbers compared with the crops in the other two soils.

Maximum grain yields were 27% lower in 1995 compared with 1994. This occurred even though the total amount of water available to the crops as stored soil water and irrigation (PAW1+Irr) was similar in both years (Table 2). The yield reductions resulted

Table 3
Cumulative evapotranspiration (ET), grain yield, total biomass, harvest index (HI), seed number, seed mass, and grain and biomass water use efficiency data for 1994

Main effect	ET (mm)	Yield		HI (%)	Yield components		Water use efficiency	
		Grain ($g\ m^{-2}$)	Biomass ($g\ m^{-2}$)		Seed no. (no. m^{-2})	Seed mass (mg $seed^{-1}$)	Grain ($kg\ m^{-3}$)	Biomass ($kg\ m^{-3}$)
Irrigation								
I-75	501a[a]	772a	1187a	65a	3200a	242a	1.54a	2.37a
I-25	444b	622b	1020b	61a	2551b	247a	1.43a	2.30a
Soil series								
Pullman	427c	616b	995b	62a	2420c	257a	1.42b	2.33a
Ulysses	527a	806a	1240a	65a	3401a	237a	1.58a	2.35a
Amarillo	463b	670b	1075b	62a	2806b	239a	1.45b	2.32a
Surface								
Mulch	473a	691a	1102a	62a	2819a	247a	1.48a	2.32a
No mulch	472a	704a	1105a	63a	2933a	242a	1.49a	2.34a

Grain yield is reported at 0% moisture.
[a]Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.

Table 4
Cumulative evapotranspiration (ET), grain yield, total biomass, harvest index (HI), seed number, seed mass, and grain and biomass water use efficiency data for 1995

Main effect	ET (mm)	Yield		HI (%)	Yield components		Water use efficiency	
		Grain ($g\ m^{-2}$)	Biomass ($g\ m^{-2}$)		Seed no. (no. m^{-2})	Seed mass (mg $seed^{-1}$)	Grain ($kg\ m^{-3}$)	Biomass ($kg\ m^{-3}$)
Irrigation								
I-100	405a[a]	561a	1126a	50a	2157a	260a	1.38a	2.77a
I-60	397a	524a	1092a	48a	2136a	245b	1.31a	2.74a
Soil series								
Pullman	378b	478b	1012b	47b	1886b	252a	1.26b	2.67a
Ulysses	435a	612a	1234a	50a	2376a	258a	1.40a	2.83a
Amarillo	391b	538b	1081b	50a	2177a	248a	1.38a	2.77a
Surface								
Mulch	412a	592a	1203a	49a	2257a	263a	1.44a	2.92a
No mulch	391a	494b	1014b	49a	2036b	242b	1.26b	2.59b

Grain yield is reported at 0% moisture.
[a]Main effect means followed by a different letter are significantly different within the main effect at the 0.05 probability level.

from the crop producing fewer seeds in 1995 compared with 1994. This was due to the high temperatures which created a high evaporative demand in 1995 following anthesis (Fig. 1), which is a critical time for determining seed number (NeSmith and Ritchie, 1992).

3.3. Water use efficiency

Mulch can increase water use efficiency (WUE), which is defined as the ratio of yield to ET, when applied and/or stored water does not evaporate but is used by the crop to produce additional biomass and

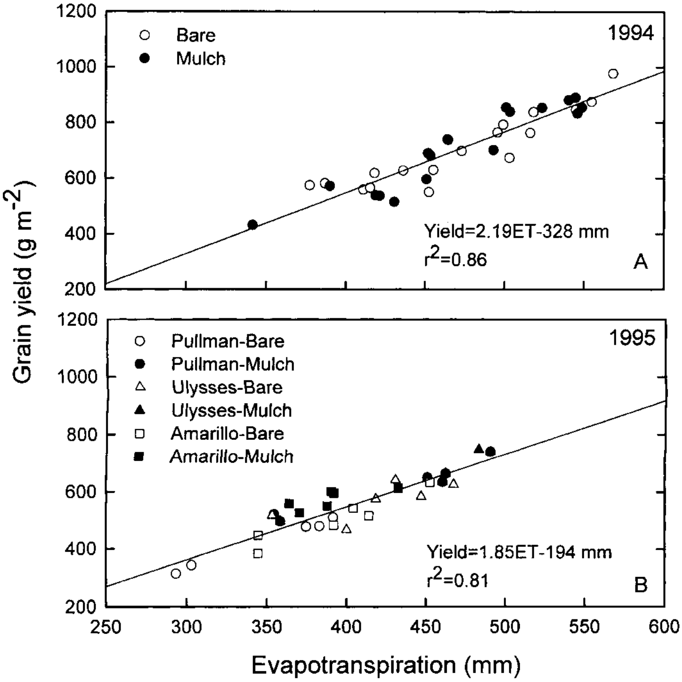

Fig. 3. Relationship between grain yield and evapotranspiration for mulched and bare soil treatments in 1994 (A), and in 1995 (B) with soil type.

Maize is sensitive to water stress, and closes stomata at higher water content of the soil compared with grain sorghum (Sanchez-Diaz and Kramer, 1971) which can reduce photosynthetic rate. In the I-60 irrigation treatment, about 30–40 mm more soil water was extracted (Table 2, PAW1-PAW2) by the mulched crops in the Ulysses and Amarillo soils compared with the bare soil crops. In the Pullman soil, over 70 mm more water was used by the mulched crop compared with the crop in the bare soil. This suggests that additional water made available to the crop by mulching the Pullman soil was important to the crop to maintain growth.

3.5. *Leaf area index*

Maximum LAI ranged from 1.1 to 1.8 for main effect treatments of irrigation, soil type, and surface mulch in 1994 (data not shown). LAI was similar between mulched and bare soil surfaces (Fig. 3(a)), except for two sampling dates prior to anthesis when LAI on the mulched surfaces was slightly higher. There were no consistent effects of irrigation treatment or soil type.

In 1995, mulching produced significantly higher (5–15%) LAI after sampling date DOY 188 (Fig. 3(b)). Maximum LAI was less variable for each main effect treatment than in 1994, but did not exceed 1.8. LAI was similar for all soil types and irrigation treatments compared with 1994. The low LAI in each experiment was due to the combination of small plant populations and reduced leaf area typical of dryland, short season maize.

4. Discussion

Mulched and bare soil treatments produced similar cumulative ETs in each year. Mulching did slow evaporation immediately following irrigations early in the season as seen in the ratios of ET from bare soil (ET_b) to ET from the mulched surface (ET_m) (Figs. 4 and 5). But, when the crop LAI approached about 1.5 (about 60 days after sowing), large differences in first-

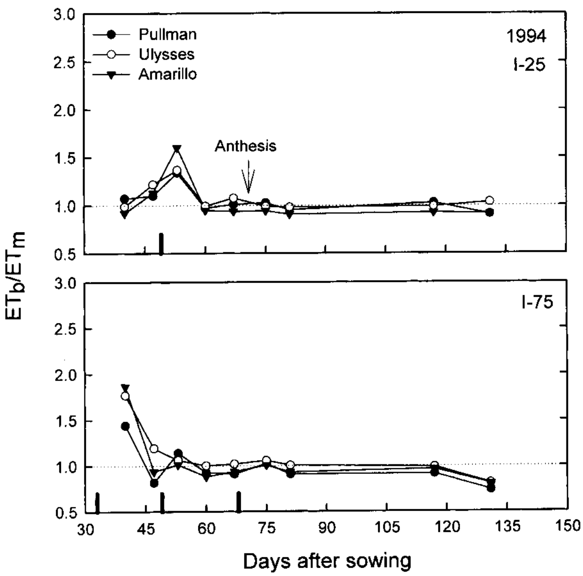

Fig. 4. The ratio of bare soil evapotranspiration (ET_b) to mulched surface evapotranspiration (ET_m) for each irrigation treatment and soil type in 1994. Vertical bars represent irrigations.

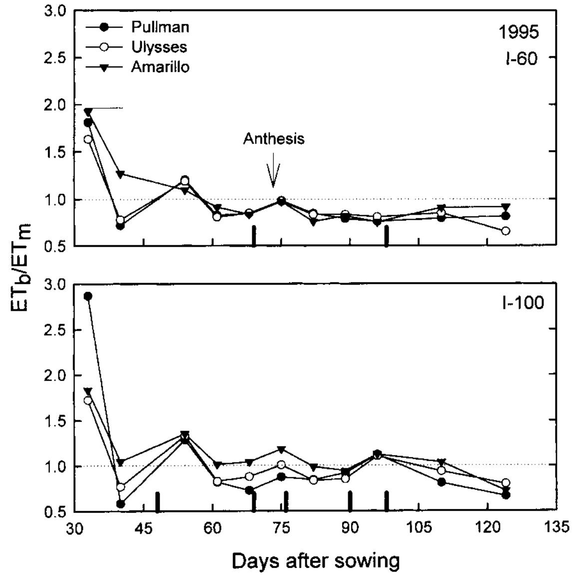

Fig. 5. The ratio of bare soil evapotranspiration (ET_b) to mulched surface evapotranspiration (ET_m) for each irrigation treatment and soil type in 1995. Vertical bars represent irrigations.

stage drying between bare soil and mulched treatments following irrigation were longer evident. This supports Todd et al. (1991), Unger and Jones (1981), and Adams et al. (1976), who found that shading by the plant canopy substitutes for the beneficial effect of a growing season mulch.

Significantly higher PAW was maintained in the mulched treatment compared with the bare soil treatments prior to maximum LAI in 1995 but not in 1994 (data not shown). This was probably due to the 68% increase in mulch mass in 1994 compared with 1995, as well as the higher evaporative demand in 1995 (Fig. 1) which increased evaporation from bare soil.

No significant differences occurred in LAI between surface treatments in the latter part of the 1994 season. In 1995, the ET of the mulched surface treatments after maximum LAI was generally greater than that of the bare soil surface, which was most likely due to the significantly higher LAI. Similar cumulative ET that year between mulched and bare soil surfaces but significantly higher LAI suggest that more water use in the mulched treatment was partitioned into transpiration and consequently plant growth rather than evaporation from the soil. The increase in total transpiration produced the significantly higher grain and biomass yields and enhanced their water use efficiencies. In a review of crop yield response to irrigation, Howell et al. (1990) pointed out the importance of improved irrigation techniques that redirected losses from evaporation, drainage, and runoff into increases in transpiration and consequently WUE.

5. Conclusions

A mulch applied during the growing season significantly increased grain and biomass yields only when it effectively suppressed evaporation of soil moisture so that most of the water was available for use by the plant. Mulch did not significantly change total water use by the crop, however. Three factors most likely interacted in 1995 to produce the more favorable soil water regime in the mulched treatment compared with the bare soil treatment: a higher evaporative demand environment, the increase in mulch mass, and the increased irrigation frequency compared with those in 1994. This suggests that environments with only a moderate evaporative demand, infrequent water applications due to limited rainfall or irrigation, or reduced mulch mass would diminish the effectiveness of mulch.

The preservation of soil moisture was especially important for maize, which is sensitive to water stress. Mulch applied during the growing season may only significantly increase yields of other crops that are more tolerant of water stress, such as grain sorghum, in extreme environmental conditions, such as high evaporative demands and very limited water.

Mulch was also important in a soil where textural characteristics affected both rooting and soil water extraction patterns. The more favorable water status created by mulch in 1995 in the Pullman soil, which had restrictive clay layers, delayed the onset of water stress and allowed more rooting and soil water use compared with the bare soil treatment. Mulching produced no significant increases in yields for the crops in the Ulysses soil in either year compared with the bare soil surface treatments. The Ulysses soil, whose fairly uniform soil horizons contained large concentrations of silt, allowed complete extraction of available water.

Many factors determined the effectiveness of mulch applied during the growing season. The magnitude of crop response was controlled by a complex interaction that varied from year to year between mulch mass, irrigation frequency, evaporative potential of the climate, and soil textural characteristics.

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